AFOSR-TR-97-0707

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
January 20, 1997

3. REPORT TYPE AND DATES COVERED
Final Technical Report 1 Aug 95 to 31 Jul 96

4. TITLE AND SUBTITLE
Development of Failure Criteria for Polymer Based Composites under Multi-axial Loading

5. FUNDING NUMBERS
F49620-95-1-0464

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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NA
110 Duncan Avenue, Room B115
Bolling AFB, DC 20332-8050

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
F49620-95-1-0464

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

19971217 049

13. ABSTRACT *(Maximum 200 words)*

Specifically, we have purchased an axial torsional MTS loading frame and accessories to complement an already existing in-house built planar multi-axial load frame. The research that the instrumentation will facilitate has three phases. In phase I, test coupons(polymer based fibrous laminated composites) that have a cruciform shape and containing a centrally located circular cutout are placed under remotely applied planar, biaxial tension(compression) proportional load states. Biaxial failure envelopes are generated as well as an identification of specific failure mechanisms and measurements such as critical strains to failure. In phase two, the specimens are loaded statically as well as under different loading rates to levels that are a fraction of the failure loads and unloaded at different loading rates, thereby characterizing the strain rate dependency and assessing a measure of damage accumulation. In phase three, the polymer(matrix material), by itself is characterized using specimens that are cylindrical under combined tension/compression and axial loading. These tests are to be performed under different temperatures and for a given temperature under different loading rates. The experiments will enable the development of analytical models with a micromechanics basis and importantly, the identification of the operative failure mechanism under different mechanical loads and in the presence of different environmental conditions.

14. SUBJECT TERMS

15. NUMBER OF PAGES
8

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

Standard Form 298 (Rev. 2-89) (EG)
Prescribed by ANSI Std. 239.18
Designed using Perform Pro, WHS/DIOR, Oct 94

DTIC QUALITY INSPECTED 3

Rec'd 1-27-97
DT

Development of Failure Criteria for Polymer Based Composites under Multi-axial Loading

AFOSR AWARD Reference No: F49620-95-1-0464
Univ. of Michigan DRDA No. 951789
Univ. of Michigan Account No. 033411

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Final Report submitted on

Jan. 20, 1997

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DTIC QUALITY INSPECTED 3

Abstract

This document constitutes the final report on work carried out under AFOSR Grant F49620-95-1-0464 for the purchase of instrumentation that is necessary to carry out experimentation for the purpose of developing failure criteria for composite materials under multi-axial loading situations in the presence of severe environmental factors. Specifically, we have purchased an axial torsional MTS loading frame and accessories to complement an already existing in-house built planar multi-axial load frame. The research that the instrumentation will facilitate has three phases. In phase I, test coupons(polymer based fibrous laminated composites) that have a cruciform shape and containing a centrally located circular cutout is placed under remotely applied planar, biaxial tension(compression) proportional load states. The coupons are placed inside an environmental chamber, where temperatures (-180 F to 600 F) can be controlled as well as the level of humidity. Biaxial failure envelopes are generated as well as an identification of specific failure mechanisms and measurements such as critical strains to failure. In phase two, the specimens are loaded statically as well as under different loading rates to levels that are a fraction of the failure loads and unloaded at different loading rates (including statically), thereby characterizing the strain rate dependency and assessing a measure of damage accumulation. In phase three, the polymer(matrix material), by itself is characterized using specimens that are cylindrical under combined tension/compression and axial loading. These tests are to be performed under different temperatures and for a given temperature under different loading rates. The experiments will enable the development of analytical models with a micromechanics basis and importantly, the identification of the operative failure mechanism under different mecahinical loads and in the presence of different environmental conditions. Such a mechanics based approach is favored over empirical approaches that have attempted to extend failure criteria developed for isotropic materials to composite materials. Characterization of the constituents under the same conditions as for the tests on the composite is seen as an integral part of the experimental program, since the individual constituent properties of the fiber and matrix need to be fed into the micromechanics based failure model development.

2. Supporting Information

a) New areas of Research

Because of the widespread use of fibrous composite structures in various load bearing applications, there is a strong need to focus on understanding the fundamental aspects of mechanical failure of these structures. Composite Materials offer several advantages over traditional materials and it is very likely that in a few years these materials will act as the primary source in industrial applications. However, properly characterizing and modeling their failure mechanisms has progressed relatively slowly, partly due to the complexity associated with the failure process. Yet, it is accepted that this task is vital if these materials are to find application in primary load bearing structures. To date, we have not found any previous research work that attempts to explore the failure mechanisms of polymer based composites under *mutiaxial loading and in the presence of extreme environments*. If composite materials are to be successfully used in primary load carrying applications, then it is crucial that we understand their mechanical behavior when subjected to extreme environments. We have described a project that combines some simple experimental studies (without sacrificing the complexity of a multi-axial load state), with the development of associated analytical models to predict the initiation of failure and damage accumulation when composite materials are placed under conditions of high temperature and humidity. The recently purchased instrumentation is vital and absolutely necessary major pieces of equipment to carry out the proposed research.

The analytical models to be developed are failure mode dependent. i.e. Each failure mechanism is identified with a separate failure mode. Therefore, the failure envelope is not a smooth curve as found for the yield of homogeneous materials (for example the von-Mises criterion), instead, it is a construct of several curves, with each curve associated with a separate failure mode. Supplementing this information are the tests and constitutive model development in connection with damage accumulation prior to failure. i.e. prior to the coupon failing, a 'virgin' composite material contains many microcracks, voids etc. that become active upon loading, but prior to failure.

A previous experimental analysis of specially prepared uni-ply `model' composite plates containing cutouts was carried out for uniaxial compressive loading under room temperature, the results of which were reported in [1,2]. Experimental results revealed failure initiation to occur at the edge of the cutout, in the form of fiber microbuckling/

kinking, followed by delamination, for specimens with hole sizes varying from the largest down to a cutoff hole size. Below this range, failure either initiated at the outer free edges, in the form of cracks, or was in the form of global (total) delamination. A finite element analysis (FEA) incorporating the experimentally obtained results was carried out utilizing the measured material properties and geometries, in order to gain insight into the in-plane failure mechanisms evident in the experimental observations.

The analysis modeled the graphite-epoxy uniply in an attempt to reproduce the results obtained experimentally. The FEA results agreed very well with the fiber buckling mode shapes from the experimental results, although the estimated buckling loads were larger than those obtained from experiments, probably due to imperfections in loading and material composition in the experiments and due to assumptions of linear constitutive laws. The trends for buckling modes and loads agree quite well for the two phases, revealing the inverse behavior between buckling load and hole size. We extended this research to room temperature biaxial loading states. We found different mechanisms of failure that become operative under different conditions. We uncovered the critical modes of failure [2], which were different than those reported in [1]. Therefore, a natural continuation of this work is to examine the mechanical behavior of such composites under extreme environments, more closely resembling what would be expected during service.

Applications that fit this category would be hypersonic vehicle structures, the high speed civil transport and multi-mission atmospheric re-entry vehicles.

Research into previous other experimental work carried out for multiaxial loading of composite plates at room or elevated temperature revealed very little published material on the subject [3-5 and 18-19]. The work that had been carried out indicated an empirical approach to the subject, rather than an approach based on mechanics. No attempt had been made to identify and quantify failure mechanisms (such as reported in [1], by the PI and colleagues). In order to keep the research as broad and general as possible, generic composite plates will be used in the investigation. From the experience and insight that we have gained from our earlier study [1], it is anticipated that the biaxial loading of composite plates will lead to a non-linear failure interaction; The loading path for composite plates under biaxial loading is path dependent, i.e. if an initial load P1 is applied along one axis of the plate, followed by a load P2 along the second axis, the behavior of the plate may be completely different than the case where the load P2 is

applied along the second axis, followed by P1 along the first axis. We wish to propose to examine the reasons why this so, and relate them to the material composition and mechanical behavior of the constituents. Such an approach is ruled in favor of an empirical one. In addition we anticipate significant rate effects to be evident in the experimental results due to the strain rate dependency of the polymer matrix. Therefore, the viscoelastic characterization of the matrix material and its incorporation into the micromechanics modeling would be an integral part of the proposed work. The viscoelastic characterization naturally necessitates tests to be carried out at different temperatures.

b.1 Research Plan

b.1.1 What is to be Done

- An experimental study using cruciform shaped specimens that contain a centrally located circular cutout and subjected to different biaxial load states, using a special purpose biaxial test frame (UM Aerospace Dept.) specifically developed for such a study. Measurement of strains around the cutout, post-experiment examination to identify specific failure mechanisms and, loading and unloading prior to failure to obtain data on "hysteresis" (damage accumulation). The specimen configuration is motivated by the need for a design where the location of failure is known a priori, and, at the same time whose stress distribution can be characterized without much difficulty. The center notched specimen configuration offers these advantages. The tests described above are to be done under different environmental conditions.

- Characterization of the constitutive response of the material from the data gathered from the loading-unloading-reloading cycles. Characterization of the damage accumulation as a function of loading rate. Incorporation of the viscoelastic nature of the polymer matrix material. Characterization of the polymer matrix material

- Development of analytical models based on items 1 and 2 above, and development of appropriate failure criteria.

- The new MTS system and the in-house Biaxial load frame are servo-controlled and fatigue rated, thus both the mechanical loads and the environmental conditions can be programmed to suit typical inflight conditions. Becuuse of this, a certain number of

experiments under programmable environmental and mechanical loading conditions will be performed.

c. Currently Proposed DOD research

Topic: *Failure Criteria for Composites*

PI: *Anthony M. Waas and Alan Wineman*

sponsor: AFOSR, 1/15/95 - 12/31/947(pending), AFOSR Contact: *Dr. Walter F. Jones*

Research Thrust: A proposal was submitted on the subject of developing failure criteria for composite materials. A combined experimental and analytical program is described . The project has three phases. In phase I, test coupons that have a cruciform shape and containing a centrally located circular cutout is placed under remotely applied planar, biaxial tension(compression) proportional load states. Biaxial failure envelopes are generated as well as an identification of specific failure mechanisms and measurements such as critical strains to failure. The tests are next repeated with the coupons placed inside an environmental chamber, where temperatures (-80 F to 140 F) can be controlled as well as the level of humidity. In phase two, the specimens are loaded statically as well as under different rates to levels that are a fraction of the failure loads and unloaded at different loading rates (including statically), thereby characterizing the strain rate dependency and assessing a measure of damage accumulation. In phase three analytical models are developed that are capable of modeling the experimentally captured failure mechanisms. The developed analytical models will have a micromechanics basis and each failure mechanism will be modeled separately. From the predictions of the models the operative failure mechanism will be identified. Such a mechanics based approach is favored over empirical approaches that have attempted to extend failure criteria developed for isotropic materials to composite materials. Characterization of the constituents under the same conditions as for the tests on the composite, will also be carried out paralleling the biaxial tests. This activity is seen as an integral part of the experimental program, since the individual constituent properties of the fiber and matrix need to be fed into the micromechanics based failure model development. The research work will commence with phase I, and will proceed as outlined above. The analytical work will parallel the experimental program. Results from the research work will be disseminated via presentations at National and International symposia and meetings, University reports and archival journal publication. It is anticipated that a research team comprising the PI's, several graduate students (a Ph.D and several masters level students) and some upper class undergraduates will be formed as a result of the activity generated under this effort.

d. Current or Proposed DOD research that is complemented

Topic: Compressive Failure of Thick Composites

PI: Anthony M. Waas

sponsor: ONR, 5/1/91 - 12/31/94 (Continuation pending), Contact: Dr. Y. Rajapakse

Research thrust: An experimental and analytical investigation was performed to study failure mechanisms of thick laminated composite rings under external pressure and radial compression. Under hydrostatic pressure via a bladder type loading the rings fail by global buckling into a n=2 oval mode. When the pressure is removed, the rings return to their original state signifying the elastic nature of the carbon (AS4)/PPS material and the Glass/Epoxy material. Under hydrostatic pressure via a O-ring type loading the rings fail by global buckling into a n=3 mode. Both these phenomena were successfully modeled. Under radial contraction, the ring material can be loaded to very high strain levels, since the geometry of the test configuration precludes global buckling. Therefore, failure in these tests occurred by fiber kinking and for the thicker rings by delamination. This latter work has uncovered several important factors that need further investigation. Amongst these are, a proper mechanical characterization of the carbon fibers, the mechanical behavior of the matrix material, the dynamic nature (rate dependency) of the kink banding process and the energy released in the formation of a kink band. Presently, we are pursuing these latter areas of research.

e. Future Prospects

Routine Stress analysis in industry is carried out via the Finite Element Method. In the design cycle, one has to input appropriate failure criteria that determines whether a certain part of the structure has failed. Inputting a criterion by itself is insufficient if the analysis is to be carried beyond the failure initiated stage. Such progressive damage accumulated modeling requires that the failure mode (details of the failed element) also be identified. We have spelled out a project that includes this feature as a major theme of the proposed work. We have outlined a research plan that uses the requested equipment to obtain crucial data on the mechanical behavior of polymer based composites under elevated temperature and humidity in a multi axial setting. The constitutive equations that can be got from such a program can be fed as input to existing FEM codes for the purpose of obtaining accurate designs. Thus, the output of the proposed work can in a straightforward way be incorporated to a commercial FEM code as ABAQUS (for example). Indeed, the Graduate Student involved in the project will have as one of his/her tasks, the

development of such a working model, that will eventually be tested via a failure prediction of a structural part and comparison with a laboratory test.

h. Useful Life of Equipment

Judging by the load frames that we currently own(purchased in the sixties), it appears that the new MTS equipment has a service life of approximately thirty years.

References

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2. Khamseh, A.R. and Waas, A.M., 1995, "Failure Mechanisms of Composite Plates under planar Biaxial Loads", to appear in Proc. Royal Soc., series A, see also, A. Khamseh, Ph.D thesis, UM Microfilm Center, 1994.